



AN INTRODUCTION TO SOIL FERTILITY

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The use of fertilizers has become a standard crop production practice on Ontario farms. Much of the credit for good crop performance is given to the fertilizer program followed by the grower. Many people believe that if fertilizer were not used, yields would fall drastically. Many also believe that much of the nutrient content of their crops comes from the fertilizer which they apply. Although the use of fertilizer is a major factor in the success of many crops, none of the above beliefs is necessarily true. Much of the nutrient content of crops comes from reserves in the soil. Even a low-testing soil can supply half or more of the nutrients needed by a crop. A high-testing soil can supply all of a crop's nutrient requirements.

The soil plays a vital role in plant nutrition, but because it contains a large assortment of elements and compounds which interact in many complex ways, soil fertility can seem very confusing. A general understanding of the way plant nutrients behave in soil can be helpful in planning a fertilizer program.

ESSENTIAL ELEMENTS OR NUTRIENTS

Most of the elements present on earth are also found in the soil, at least in trace amounts. Relatively few of them are important to crops. (The most common elements in plants – carbon, hydrogen and oxygen – are obtained from the air and water.) Only thirteen elements found in the soil are essential for plant growth (Table 1). Crop growth or quality will be adversely affected if these essential elements, or nutrients, are not available in quantities

sufficient to meet crop requirements. Nutrients that are required by crops in relatively large amounts are sometimes called macronutrients. Those required in very small amounts are known as micronutrients or trace elements. Those that fall in between are called secondary nutrients.

TOXICITIES

Several elements can have adverse effects on plants. Iron, aluminum, boron, copper and manganese all can be toxic to plants if present in too large an amount. Other elements, when present in too large a quantity, interfere with the uptake of essential nutrients. For example, an excess of phosphorus can reduce the availability of zinc and over-use of potassium can reduce the uptake of magnesium. Thus, soil must be managed to ensure an adequate supply of the essential nutrients, while minimizing the adverse effects of certain elements.

ORIGINS OF SOIL FERTILITY

Nutrients exist in the soil in a variety of forms, of which only a few are useful to plants. Originally, most of the nutrients in soil comprised part of the chemical structure of the rocks and minerals from which the soil was derived. Much of the total nutrient content of soil remains in this form and as such, is not available for uptake by plants.

The natural fertility of a soil is determined both by the type of rock from which the soil was derived and by the conditions under which it was formed. In the 10,000 or so years since the glaciers retreated from Ontario, various natural forces have broken down some of the soil minerals releasing their nutrient content in forms available to plants. These forces, collectively known as weathering, include wind, water, frost, micro-organisms, and naturally occurring acids. Since soil continues to be subject to weathering, small amounts of available nutrients are continually being released in the soil.

Most of the nitrogen in soil is derived from the air rather than rock. Air is about 80% nitrogen gas, but it cannot be used directly by plants. Some soil bacteria can convert nitrogen gas into an organic form through nitrogen fixation. When the organic matter decomposes, the nitrogen becomes available to plants. Nitrogen fixation is the main natural source of soil nitrogen. (A small amount of nitrogen

Table 1 Essential Plant Nutrients

Macronutrients		Micronutrients	
Nitrogen	(N)	Boron	(B)
Phosphorus	(P)	Chlorine	(Cl)
Potassium	(K)	Copper	(Cu)
		Iron	(Fe)
		Manganese	(Mn)
Secondary Nutrients		Micronutrients	
Calcium	(Ca)	Molybdenum	(Mo)
Magnesium	(Mg)	Zinc	(Zn)
Sulphur	(S)		

falls in the rain after having been converted from nitrogen gas to nitrate by lightning. Some nitrate nitrogen is also contained in acid rain.)

IONS

Part of the nutrient content of soil is in the form of ions. An ion is an atom or molecule which has acquired an electrical charge. Positively charged ions are called "cations". Elements that form cations in soil include hydrogen, potassium, calcium, magnesium, nitrogen (as ammonium), zinc, iron, copper, manganese, sodium and aluminum. Negatively charged ions are called "anions". Elements that form anions in the soil include nitrogen, phosphorus, sulphur, boron, chlorine, and molybdenum. The anions formed by these elements are called nitrate, phosphate, sulphate, borate, chloride, and molybdate, respectively. (The "-ate" suffix indicates that the element is combined with oxygen.)

THE SOIL SOLUTION

The mixture of soil moisture and the various materials dissolved in it is known as the soil solution. For the most part, only nutrients ions dissolved in the soil solution are available for uptake by plants. These, however, comprise only a small fraction of the total nutrient content of soil - often less than one percent.

Ions are continually being added to the soil solution by weathering and from decomposing organic matter, but there are also several means by which they are removed again.

- Nutrients dissolved in the soil solution move with the moisture. Thus, some can be lost from the soil in the drainage water. This is known as leaching. In periods of high rainfall, significant amounts of soluble nutrients can be lost by leaching, especially on coarse textured soils.
- In wet soils, bacteria convert nitrates to nitrogen gas through a process called denitrification. The nitrogen is then lost to the atmosphere.
- Potassium can be trapped temporarily within the structure of some of the clay particles. (This portion of the soil potassium is said to be "fixed" or "difficultly available", since it is released again only with further weathering.)
- Phosphates react with other elements, such as calcium, iron, zinc, aluminum and manganese, to form insoluble compounds that are unavailable to plants until weathered.
- Nutrients taken up by plants or soil micro-organisms become part of the soil organic matter and are unavailable until it decomposes.

All of the above processes occur continually. There is an interchange of nutrients among the various forms such that a rough balance exists among them. Nutrients removed from the soil solution by plants or by leaching are gradually replaced by those released from the less available forms. Conversely, nutrients added to soil in fertilizer are converted to less available forms until the balance is re-established.

The nutrients in most fertilizers are readily available. In soil, however, they start to react almost immediately and are converted to less available forms. Of the nutrients applied in fertilizer, only a small proportion is captured by the crop in the year of application. About 50% to 70% of the applied nitrogen, 10 to 20% of the phosphorus, and 20 to 30% of the potassium are taken up by the crop in the year of application. Most of the rest of the phosphorus and potassium is held in the soil. Therefore, one result of the use of fertilizer, even at recommended rates, is that soil fertility gradually increases.

However, changes in fertilizer management are often not reflected in the soil test as quickly as one might think. Building up soil fertility is a slow process. Soil tests measure only the nutrients that are available to crops, and much of what is applied becomes unavailable, at least temporarily. Conversely, the presence of these reserves means that one might grow crops for several years on some high-testing soils without applying a particular nutrient before there is a change in the soil test. The rate at which the soil test changes varies from field to field and depends on the nutrient holding capacity of the soil.

NUTRIENT HOLDING CAPACITY

Because only a small amount of nutrients are actually dissolved in the soil solution, the available fertility would be quickly depleted if there were not some means of protecting them from being lost or of replacing those that are removed. The nutrient holding capacity of soil is determined largely by its composition. Of prime importance are the amounts and types of clay and humus present, since these are the most reactive fractions of soil. Both exist as very finely divided particles with large surface areas (Chemical reactions occur almost exclusively on the surface of any object. The more surface area a substance has, the more reactive it is.) Furthermore, because of the way in which they were formed, particles of both clay and humus carry negative electrical charges. These are a major factor in determining a soil's nutrient holding capability.

CATION EXCHANGE

Although clay and humus particles are negatively charged, the soil, as a whole, must be neutral. Through the natural attraction of opposite charges, cations are drawn to the surface of soil particles until the charges are neutralized. Cations held on soil particles in this way are said to be "Adsorbed".

Adsorbed cations are held tightly enough to resist removal by leaching, but they can be removed by plant roots or be replaced by other cations. The replacement of an adsorbed cation by another from the soil solution is called "cation exchange". Adsorbed cations are, therefore, said to be "exchangeable" and the locations where cations are held are called "exchange sites". Exchangeable nutrients are readily available for uptake by plants, either directly, if a root touches the exchange site, or after

entering the soil solution via the exchange process. Since far more nutrients are held on exchange sites than are in the soil solution, exchangeable nutrients represent a very important reserve of soil fertility, especially for calcium, potassium and magnesium.

The electrical neutrality of the plant-soil system must be maintained as plants take nutrients from the soil solution. When a plant takes up a nutrient cation, a cation of another element must be put back into the soil solution. Usually, this is a hydrogen cation. Similarly, cations removed from an exchange site must be replaced. Again, the replacement is usually an hydrogen cation. Thus, soils gradually become more acidic as a natural consequence of plant growth. (See OMAF Factsheet, *Soil Acidity and Liming*, Agdex # 534.)

The ability of a soil to hold cations is known as its "cation exchange capacity" (CEC). Soils that contain a large amount of clay or organic matter have a relatively high CEC. The CEC of a soil can be measured with a special soil test. However, it is usually sufficient to know that the fertility of soils with a low content of clay or humus, such as sand and sandy loams, can change quickly if the soil is not fertilized properly and that regular testing of such soils is essential.

The CEC of humus varies with the pH of the soil. Under very acidic conditions (pH under 4), humus carries little, if any, charge. As the pH increases, the chemical structure of humus changes slightly so that the amount of charge increases. Under slightly alkaline conditions (pH 7 to 8), humus is highly charged. Thus, the CEC of an acid soil can usually be increased by liming.

BASE SATURATION

Calcium, magnesium, potassium and sodium are elements that are alkaline or basic in nature, because they tend to neutralize acidity. In soil, they are often referred to as "basic cations" or as "exchangeable bases" (to contrast with hydrogen and aluminum, which are acidic). The proportion of a soil's CEC that is occupied by calcium, magnesium, potassium and sodium is known as the "percent base saturation". For most soils, the percent base saturation should be relatively high (over 80%) to ensure an adequate supply of these nutrients. However, it is usually not necessary to measure the per cent base saturation, because of its strong relationship to soil pH. (The percent base saturation decreases as soil becomes more acidic.) If the soil pH is maintained in the appropriate range for the crop being grown, the base saturation should also be satisfactory.

ANION RETENTION

In Ontario's soils, there is no system of anion exchange comparable to cation exchange. Nutrients that form anions are held in the soil by other mechanisms, and for most, only a small proportion is maintained in available forms.

The main reserve of nitrogen in soil is in the organic matter. Organic nitrogen cannot be used directly by plants,

but it becomes available gradually over the growing season as the organic matter decomposes.

Plants take up most of their nitrogen as nitrate. (They can also take up nitrogen in the ammonium form, but ammonium nitrogen in soil is usually converted to the nitrate form very quickly.) At times, there can be a considerable amount of nitrate nitrogen in the soil especially in warm, moist weather when the breakdown of organic matter is greatest. Under dry conditions, there can also be carryover of nitrate nitrogen from the previous year, especially if large amounts of nitrogen had been applied. There is, however, no means of holding nitrogen in the nitrate form in the soil in wet weather. Nitrates are water soluble and readily leached away, especially on sandy soils. They also can be lost from saturated soils by denitrification. Thus, levels vary greatly over the growing season depending on the weather.

Phosphorus moves very little through soil, so leaching is not a major concern. (There is relatively little loss of phosphorus from soil except through soil erosion.) However, very little of the phosphorus in soil is available to plants. Phosphate anions are very reactive and combine quickly with other elements to produce compounds that are insoluble. In neutral or alkaline soils, phosphates react with calcium; in acid soils, they react with iron, manganese, and aluminum. The phosphorus in these compounds gradually becomes available again as they are broken down by weathering.

Some phosphorus is also contained in the soil organic matter, but the conversion of organic phosphorus to available forms is a slow process, especially in cool soils. Available phosphorus levels are most often of concern in the early spring, for spring-seeded crops, or in late fall, for fall-seeded crops.

NUTRIENT MOBILITY AND FERTILIZER PLACEMENT

Because nitrogen and phosphorus behave very differently in the soil, the fertilizers supplying these nutrient should be managed differently to be most effective. Nitrates move readily in the soil if there is adequate soil moisture. As long as a plant is taking up water, nitrates move to the roots. Nitrogen does not need to be placed close to the roots for plants to obtain it. (Indeed, placement of large amounts of nitrogen close to the seed should be avoided because of the potential for damage. See section on Toxicity of Fertilizer Materials in OMAF Publication 296 Field Crop Recommendations.)

In contrast, because phosphorus moves very little in the soil, roots can obtain this nutrient only if they grow to where it is located. The most efficient way to apply phosphorus is to place it near the plant where the roots can reach it before it becomes fixed. This is most beneficial early in the growing season when root systems are small and the release of phosphorus from the soil is slow. For many crops, seedling growth is enhanced by applying a

small amount of phosphorus fertilizer near the seed at planting, even on relatively fertile soils. Fertilizer applied in this fashion is often referred to as "starter". Uptake of phosphorus is improved if a small amount of nitrogen is also included in the starter fertilizer. Where large amounts of phosphorus are required, it is often most practical to apply a small amount as starter and to broadcast the rest.

Potassium is intermediate in mobility between nitrogen and phosphorus. Thus, the effect of placement is not as great as with phosphorus. Broadcast applications are usually as effective as banded treatments, except on low-testing soils where there can be an advantage to including some potassium in the starter.